ON NOETHER'S RATIONALITY PROBLEM FOR CYCLIC GROUPS OVER $\mathbb{Q}$

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Abstract. Let p be a prime number. Let C_p, the cyclic group of order p, permute transitively a set of indeterminates $\{x_1, \ldots, x_p\}$. We prove that the invariant field $\mathbb{Q}(x_1, \ldots, x_p)^{C_p}$ is rational over $\mathbb{Q}$ if and only if the $(p-1)$-th cyclotomic field $\mathbb{Q}(\zeta_{p-1})$ has class number one.

1. Introduction

Let a finite group G act regularly on a set of indeterminates $\{x_1, \ldots, x_n\}$ and let k be a field. *Noether's problem for G over k* asks whether the field extension $k(x_1, \ldots, x_n)^G/k$ is rational, i.e. purely transcendental.

The present note deals with Noether's problem for finite cyclic groups over the field of rational numbers. The reader is referred to [3] for a brief survey of Noether's problem for abelian groups, including the most relevant references to work of Masuda, Swan, Endo, Miyata, Voskresenski, Lenstra and others.

Let $P_{\mathbb{Q}}$ denote the set of prime numbers p for which $\mathbb{Q}(x_1, \ldots, x_p)^{C_p}/\mathbb{Q}$ is rational, where C_p denotes the cyclic group of order p.

Lenstra proved in [4, Cor. 7.6] that $P_{\mathbb{Q}}$ has Dirichlet density 0 inside the set of all prime numbers. Moreover, he suggested in [5, p. 98] that $P_{\mathbb{Q}}$ could be finite and that perhaps coincides with the set

$$R := \{2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 61, 67, 71\}.$$

It is known that $R \subseteq P_{\mathbb{Q}}$. This is a consequence of the fact that, by the main result in [6], R is nothing but the set of prime numbers p such that the $(p-1)$-th cyclotomic field $\mathbb{Q}(\zeta_{p-1})$ has class number one.

For prime numbers $p < 20000$, some computational evidence in favour of the equality $P_{\mathbb{Q}} = R$ is given by Hoshi in [3].

Our goal is to check the validity of Lenstra's suggestion. We prove:

Theorem 1.1. *$P_{\mathbb{Q}} = R$.*

From [5, Cor. 3] and [5, Prop. 4], we get:

Corollary 1.2. *Let n be a positive integer and let C_n denote the cyclic group of order n. Then $\mathbb{Q}(x_1, \ldots, x_n)^{C_n}/\mathbb{Q}$ is rational if and only if n divides*

$$2^2 \cdot 3^m \cdot 5^2 \cdot 7^2 \cdot 11 \cdot 13 \cdot 17 \cdot 19 \cdot 23 \cdot 29 \cdot 31 \cdot 37 \cdot 41 \cdot 43 \cdot 61 \cdot 67 \cdot 71,$$

for some $m \in \mathbb{Z}_{\geq 0}$.

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2. Proof

Proof of Thm. 1.1. As has already been mentioned, the inclusion $R \subseteq P_{\mathbb{Q}}$ is known. See [2, Prop. 3.4].

Let $p \in P_{\mathbb{Q}}$. This implies (actually, it is equivalent to) the existence of an element $\alpha \in \mathbb{Z}[\zeta_{p-1}]$ with norm $N_{\mathbb{Q}(\zeta_{p-1})/\mathbb{Q}}(\alpha) = \pm p$. See [2, Thm. 3.1].

Thus, $\mathfrak{p} = (\alpha)$ is a principal prime ideal in $\mathbb{Z}[\zeta_{p-1}]$ above (p).

If $\mathrm{Gal}(\mathbb{Q}(\zeta_{p-1})/\mathbb{Q}) = \{\sigma_1, \dots, \sigma_m\}$, then we have the prime ideal decomposition

$$(p)\mathbb{Z}[\zeta_{p-1}] = \sigma_1(\mathfrak{p}) \cdots \sigma_m(\mathfrak{p}).$$

Here $m = [\mathbb{Q}(\zeta_{p-1}) : \mathbb{Q}] = \phi(p-1)$, where ϕ denotes Euler's totient function. Note that (p) splits completely in $\mathbb{Q}(\zeta_{p-1})$, hence $\sigma_i(\mathfrak{p}) \neq \sigma_j(\mathfrak{p})$ for $i \neq j$.

Now, a result of Amoroso and Dvornicich [1, Cor. 2] ensures that

$$\frac{\log(p)}{\phi(p-1)} \geq \begin{cases} \dfrac{\log(5)}{12}, & \text{for every } p, \\ \dfrac{\log(7/2)}{8}, & \text{for every } p \not\equiv 1 \pmod 7. \end{cases}$$

It may be worth mentioning here that we are not assuming that $\mathbb{Q}(\zeta_{p-1})$ contains an imaginary quadratic subfield, even though this hypothesis is apparently used in the proof of [1, Cor. 2]; in fact, if $\overline{\alpha}$ denotes the complex conjugate of α, then the argument in [1, Cor. 2] works whenever $(\alpha) \neq (\overline{\alpha})$, and this holds because (p) splits completely in $\mathbb{Q}(\zeta_{p-1})$.

On the other hand, from a result of Rosser and Schoenfeld [7, Thm. 15], we also know that

$$\frac{\log(p)}{\phi(p-1)} < \frac{\log(p)}{p-1}\left(e^C \log(\log(p-1)) + \frac{5}{2\log(\log(p-1))}\right),$$

where $C \approx 0.57721$ denotes Euler's constant.

If $f(p)$ denotes the right hand side of the above inequality, it is easily checked that $f(x)$ defines a decreasing function for, say, $x > 43$. Since $f(173) < \frac{\log(5)}{12}$, we conclude that $p < 173$.

Once we restrict ourselves to prime numbers $p < 173$, Hoshi's computations [3] show that the only possible counterexamples to the inclusion $P_{\mathbb{Q}} \subseteq R$ are 59, 83, 107 and 163.

Finally, each $p \in \{59, 83, 107, 163\}$ satisfies

$$p \not\equiv 1 \pmod 7 \quad \text{and} \quad \frac{\log(p)}{\phi(p-1)} < \frac{\log(7/2)}{8},$$

hence $p \notin P_{\mathbb{Q}}$.

$\square$

Remark 2.1. Let $n = p^r$ for some prime number $p \geq 5$.

Lenstra proved [5, Lemma 5] that $\mathbb{Z}[\zeta_{\phi(n)}]$ contains no element of norm $\pm p$ in the following cases:

(i) $p \geq 11$ and $r \geq 2$.
(ii) $p \geq 5$ and $r \geq 3$.

Then, by [2, Thm. 3.1], $\mathbb{Q}(x_1, \dots, x_n)^{C_n}/\mathbb{Q}$ cannot be rational in these cases [5, Prop. 4].

Arguing as in the proof of Theorem 1.1, one can easily prove Lenstra's Lemma as follows.

If $\alpha \in \mathbb{Z}[\zeta_{\phi(n)}]$ has norm $\pm p$, then $\mathfrak{p} = (\alpha)$ is a principal prime ideal above (p) whose inertia degree over (p) is 1. Since (p) splits completely in $\mathbb{Z}[\zeta_{p-1}]$, it must be $\mathfrak{p} \neq \overline{\mathfrak{p}}$. It follows that Amoroso and Dvornicich's result [1, Cor. 2] applies and it ensures that

$$\frac{\log(p)}{\phi(\phi(n))} \geq \frac{\log(5)}{12}.$$

But it is readily seen that this inequality does not hold in cases (i) and (ii), just checking that:

1) In case (i), $\dfrac{\log(p)}{\phi(\phi(n))} \leq \dfrac{\log(p)}{2(p-1)} \leq \dfrac{\log(11)}{2 \cdot 10} < \dfrac{\log(5)}{12}$.
2) In case (ii), $\dfrac{\log(p)}{\phi(\phi(n))} \leq \dfrac{\log(p)}{p(p-1)} \leq \dfrac{\log(5)}{5 \cdot 4} < \dfrac{\log(5)}{12}$.

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